The Harvest of Biological Production as a Means of Improving Effluents from Sewage Lagoons

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THE HARVEST OF BIOLOGICAL PRODUCTION AS A MEANS OF IMPROVING EFFLUENTS FROM SEWAGE LAGOONS

by

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RESEARCH PROGRAM FOR THE ABATEMENT
OF MUNICIPAL POLLUTION WITHIN THE
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ABSTRACT

The feasibility of removing phosphorus, nitrogen and organic matter through the harvesting of algae, duckweed (*Lemna sp.*), daphnia (*Cladocera*) or midge larvae (*Tendipedidae*) has been examined using analytical information from five Ontario sewage lagoons and information on production and chemical composition of the biota derived from the literature. Effluent analyses showed that an average of 1.7 ppm more total phosphorus must be removed to meet a 1 ppm total phosphorus standard for effluents. Harvesting part of the algae or duckweed crop could provide this reduction. Production figures from the literature indicate daphnia culture would provide the necessary removal from two of five lagoons. One instance where midge larvae production for an Ontario lagoon could be calculated indicated that a three-fold increase in standing crop would be required. Daphnia and midge larvae would provide immediately useful products for fish culture, the value of which could be used to offset part of harvesting and sewage treatment costs. Possible means of increasing production and harvesting methods are discussed in this report. The culture and harvest of aquatic organisms provide additional benefits through the removal of nitrogen and other sewage constituents, and their culture is proposed as a possible alternative to the chemical precipitation practices currently in use.

RÉSUMÉ

L'auteur a étudié la possibilité d'éliminer le phosphore, l'azote et la matière organique des eaux usées par le moyen de la récolte des algues, des lenticules (*Lemma sp.*) et des larves de daphnies (*Cladocera*) ou de moucherons (*Tendipedidae*) qui y vivent. Cette étude est basée sur des données analytiques provenant de cinq étangs d'eaux usées de l'Ontario, et de renseignements provenant de publications concernant la production et la composition chimique de la matière vivante. L'analyse des effluents a montré qu'il était nécessaire d'abaisser, en moyenne, la concentration du phosphore de 1.7 ppm pour satisfaire à la norme établie à 1 ppm pour le phosphore total. La récolte d'une partie des algues ou des lenticules pourrait permettre d'obtenir cette réduction. Les données tirées des publications montrent que l'élevage des daphnies pourrait permettre d'obtenir la réduction nécessaire dans deux ou cinq des étangs. Le calcul de la production de larves de moucherons d'un étang de l'Ontario a montré qu'il serait nécessaire d'en tripler la population. Les larves de daphnies et de moucherons seraient immédiatement utilisables en pisciculture, ce qui permettrait de réduire les coûts de récolte et ceux du traitement des eaux. On trouve dans le rapport une analyse des moyens possibles d'améliorer les méthodes de production et de récolte. L'élimination de l'azote et d'autres constituants des égouts par la culture et la récolte d'organismes aquatiques a des avantages secondaires, et on propose cette méthode comme solution de rechange possible à la précipitation chimique actuellement utilisée.

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1. INTRODUCTION

The sewage lagoon is a simple biological system in which the organic loading during the open water season is reduced through bacterial degradation under aerobic conditions. The oxygen required is supplied through photosynthesis and surface aeration. The degraded organics supply phosphorus, nitrogen and carbon, and these, together with the energy of sunlight, provide a rich medium for the culture of algae. Under conditions of heavy organic loading, this simple symbiotic relationship between the algae and the bacteria comprises the principal biological system. Additional steps are precluded by frequent anoxic periods and high levels of toxic by-products which prevent the development of more sensitive forms of life.

Under less severe organic loading conditions, anoxic periods in the ponds are less frequent and prolonged and a limited number of pollution-tolerant animal species, midges (*Tendipedidae*) and daphnia (*Cladocera*) are able to populate the system. Under still lighter loadings, a much wider group of less tolerant organisms can survive and a more complex biological system develops. This chain of events is frequently seen where three ponds operate in series.

Under heavy organic loading, warm temperatures and bright sunlight, the production of algae is extremely high. Production is limited only by the availability of light, which the density of algae determines, and factors such as auto-toxins produced by the algae themselves. Small environmental changes such as cloudy days tip the oxygen balance between photosynthesis and respiration, and the whole system frequently becomes anaerobic.

To bring some degree of balance into lagoon systems, loadings are adjusted so that the pond can operate with a balance in favour of aerobic conditions. The production of algae at such loadings is still very high, and the environmental conditions created approximate the level where midge larvae or daphnia can begin to colonize the environment. Like the algae, those animal species that can tolerate the conditions, find an unlimited supply of food and an environment that prevents the establishment of their predators and competitors. Without natural controls, their numbers and production far exceed anything found under natural conditions and their

populations are limited only by space or toxins produced by the animals themselves or the organisms with which they are associated.

If sufficient control could be maintained on the system and the ponds managed for the maximum production of harvestable organisms, the possibility exists that sufficient biomass could be removed, together with the phosphorus, nitrogen and organics that it contains, to provide a much improved effluent. In addition, the products harvested have a value and this could be used to offset the costs of treating the sewage and harvesting the product.

To achieve this objective, an understanding of environmental constraints and requirements of the organisms to be cultured must be determined and means devised to control the system. Potential production must be determined and an economical means of harvesting and processing the product devised so that the benefits outweigh the costs.

A number of studies have been made of the biological processes and environmental constraints within sewage lagoons, and some production figures are available. Other studies have provided information on the chemical analysis of the inhabitants. Some estimates have been made of the benefits to effluents through the removal of algae production, but a means of harvesting the minute algal forms has not been developed and will be difficult and costly. Why not then use the herbivores to transform the algae into animal protein and remove them? Existing technology should permit economical harvesting and the product is of known economic value.

Under terms of the United States of America and Canada, Water Quality Agreement (1972), each country agreed to limit the phosphorus content of sewage discharges to the Great Lakes to 1 ppm. In assessing the feasibility of culture and harvest as a means of nutrient removal, an objective of 1 ppm phosphorus has been used.

Conclusions on the reductions of nitrogen and phosphorus that might be anticipated through a harvesting program are based on the premise that the plant nutrients removed are in excess of those precipitated by normal lagoon processes. Information is not available to either support or refute this premise. The report is a feasibility study and a number of questions with respect to its practicability remain open, including the validity of predicted nutrient removals. The answers to these must await a well-controlled experiment under practical field conditions.

2. THE BIOTA AND ENVIRONMENT OF SEWAGE LAGOONS

2.1 Algae

During the open water season, sewage lagoons may vary in appearance from a light grey-green to a brilliant deep green colour, depending upon the state of the algae population. The forms inhabiting sewage lagoons are typically small species belonging to the green algae class (*Chlorophyceae*). The genera most commonly produced in Ontario lagoons and elsewhere are *Chlamydomonas sp.*, *Scenedesmus sp.* and *Chlorella sp.*

The composition of algae is in a ratio of approximately 25 parts carbon, four parts nitrogen and one part phosphorus. In order to obtain the maximum yield and, therefore, the greatest removal of phosphorus, carbon and nitrogen resources must be present in excess of minimum requirements. Fitzgerald (1958) estimated that only slightly more than half of the carbon requirement for maximum production is supplied in sewage. Bicarbonates and CO_2 from the atmosphere augment the supply but still may not provide the total requirement. The wide diurnal fluctuations in pH commonly noted in the ponds indicates that carbon resources are in short supply during periods of intense photosynthesis. The carbon resource in raw sewage is greater than in treated effluents from conventional processes and is, therefore, a better feed for sewage lagoons.

The majority of the nitrogen provided by the degradation of raw sewage is in the ammonia form, which is suitable for direct use by the algae, and is generally in balance with phosphorus concentrations.

Sunlight is the fuel that drives the photosynthetic engine. Long hours of sunlight increase production and, conversely, short days or heavy cloud cover reduce production. Periods of anaerobic conditions are frequently brought about by several cloudy days in succession when the net oxygen production is less than that required for respiration by the bacterial and algal flora. Auto-shading by a high standing crop reduces the penetration of light and hence production, even though a very large biomass may be present. While grazing or harvesting will reduce the standing crop, it will increase production by maintaining active growth in the remaining population.

2.2 Duckweed

Duckweed (*Lemnaceae*) has been suggested as a means of nutrient removal and production from sewage effluents, (Ehrlich, 1964; Harvey, and Fox, 1973; and Dinges, 1973). This plant grows very rapidly under organically enriched conditions and lends itself to continuous culturing and harvesting by conventional techniques. Duckweed is not found on conventional sewage lagoons and a cursory search of the literature did not provide a good description of growth requirements or culture techniques. Harvey and Fox (1973) examined the ability of *Lemna minor* to remove nutrients from sewage. They grew duckweed in aquaria supplied with filtered raw sewage. Kjeldahl nitrogen removals of 75% to 89%, nitrate-nitrogen removals of 21% to 60% and phosphorus removals 56% to 81% were recorded.

Submerged and emergent vascular aquatic plants have been suggested for use in improving effluents from sewage treatment facilities. These may have a place in polishing final effluents but are unsuitable for growth in the primary treatment stages because of their inability to compete with algae for light and the unfavourable environment that exists at conventional loadings.

2.3 Zooplankton

Daphnia (*Cladocera*) are the largest (1-3 mm) and most evident zooplankton form in sewage lagoons. Rotifers and copepods also attain high numbers, but are smaller and would be difficult to remove in a harvesting program. The *Cladocera* reported from lagoons included *Daphnia magna*, *Daphnia pulex*, *Daphnia similis* and *Moina rectirostris*. The culture of daphnia has long interested biologists because of the important role they play in fish culture. There is, however, little experimental information on the culture and the production of maximum biomass of daphnia in sewage ponds.

Reproduction is parthenogenic (development from unfertilized eggs) during most of the year when environmental conditions are favourable. In our climate, large populations in ponds generally occur in spring and fall. Dinges (1973) reported that daphnia production began when the photoperiod was less than 500 minutes and a mean air temperature less than 70° F. During unfavourable conditions "resting" eggs are

produced in a thick capsule that is capable of withstanding drying and freezing. In this way they can repopulate sewage lagoons when favourable conditions return. In an actively reproducing population, adults may release eggs every two days and maturation from egg to adult occurs in about six days.

Daphnia are filter feeders. Food is swept from the water and the stream of filtered particles are fed to the mouth parts. Particles selected include algae, protozoans, organic detritus and bacteria so that, in sewage lagoons, sewage solids and bacteria are consumed, aiding in the treatment process. Ehrlich (1964) reported a 90% reduction in coliform bacteria in cultures containing daphnia.

It is not fully understood why some waste stabilization ponds contain dense populations of daphnia while others do not. Daphnia have been found to be susceptible to prolonged anoxic conditions, toxic soluble sulphides and ammonia under high pH conditions.

Wide fluctuations in pH values occur in many sewage lagoons during periods of bright sunlight and intense photosynthetic activity. Dinges (1973) observed that a pH range of 6.5 to 8.5 was acceptable to daphnia and attributed adverse effects above 8.5 to ammonium toxicity. At low pH levels (i.e. below 7.2) and low temperature, most of the ammonia present is in the ionic form of NH_4^+, which is relatively nontoxic to aquatic organisms. As the pH or temperature increases, the ionized ammonia changes to unionized ammonium hydroxide, $NH_4(OH)$, which is toxic to daphnia. Dinges found pH-ammonia relationships to be the primary chemical factor influencing daphnia populations in stabilization ponds. It was also noted that *Daphnia magna* is more tolerant than *Daphnia pulex* to high pH.

Soluble sulphides are a second toxic factor affecting daphnia in sewage lagoons and are produced by sulphate-reducing bacteria under anaerobic conditions. Daphnia can tolerate a hydrogen sulphide level of 3.0 ppm, but production is best if the level is below 0.4 ppm.

Where toxic conditions can be prevented, daphnia can tolerate quite heavy organic loading. In the Eldorado, Texas stabilization pond, daphnia were observed at the inflow to the pond from an Imhoff aeration

tank, and at Nazareth, daphnia were seen feeding directly on particulate matter at the raw sewage inflow. One 30-acre pond serving part of Austin, Texas received the combined effluent from a raw sewage aeration basin and an activated sludge plant, and daphnia at the inflow were observed to be large and healthy and contained many embryos. BOD loading data for ponds which supported daphnia populations are as follows: 43-47 lb/acre/day at Riverside, Texas, 30-55 lb/acre/day at Longview, Texas, 73 lb/acre/day at Tracy, Texas and 161 lb/acre/day at Shastina, Texas.

Daphnia can tolerate low dissolved oxygen conditions and short periods when no detectable D.O. is present. Oxygen supersaturation is believed to be harmful, but this may be a symptom of excessive photosynthesis causing elevated pH and unfavourable concentrations of unionized ammonia.

Ryther (1954) found that the feeding rates of daphnia were inhibited by heavy concentrations of phytoplankton. It was also reported that the feeding rate was inversely proportional to the age of the phytoplankton population. The ideal food of daphnia is young, actively dividing phytoplankton. If the phytoplankton populations grow faster than can be consumed by daphnia, and the algae become senescent, a substance is produced by the algal cells which inhibits grazing rates and reproduction. This substance is believed to be the antibiotic chlorellin.

2.4 Midges

Midge larvae (*Tendipedidae*) found in sewage lagoons are the immature stage of the dipterid (two-winged flies) commonly called gnats. These insects are frequently seen swirling around in small clouds along the shores of lakes and ponds. While there are a great many species of midges, only a few are sufficiently tolerant of the polluted conditions in sewage lagoons to be able to survive. Midges most commonly reported in sewage ponds in temperate climates include *Glyptotendipes barbipes*, *Chironomus plumosis*, *Tanypus punctipenis* and *Chironomus reparius*.

The majority of midge larvae populating sewage lagoons are herbivores that graze on the abundant algal crop. Shortly after

hatching, larvae spin a tube of silk and detritus slightly larger than the body diameter. A net is then spun over the opening to the tube, and water is pumped through by an undulating movement of the body. The net filters out the algae and when the net is full, it is consumed, a new net is constructed and the process repeated. Measurements made by Tubb and Dorris (1965) in laboratory cultures using water from sewage lagoons showed that algae numbers were reduced 20%-30% by the larvae.

The life history of the midge begins when fertilized eggs are laid by the female on the pond surface or attached to grasses at the edge of the pond. The eggs hatch in one and a half to three days and the larvae immediately build their tube and commence feeding. Depending on the species, they go through three to five instars (moults). When the larval stage is complete, they pupate and in about one week emerge as adults. The swarming of gnats is part of a breeding process in which the female flies into the swarm, is fertilized and shortly thereafter deposits her eggs to complete the cycle.

The development period from egg to adult varies according to the species, temperature, food and water quality in the pond. Generally, however, the cycle is completed in 20 to 50 days. Several authors have noted a seasonal succession of the dominant species.

Midge larvae found in lagoons are pollution tolerant species capable of living in low oxygen conditions. They are red in colour, hence the erroneous name "bloodworms". The red colour comes from a pigmented body fluid containing a substance similar to haemoglobin that has a high efficiency for oxygen exchange. This special adaptation enables them to survive where others cannot.

Midge larvae are tolerant to a number of the physical and chemical stress factors found in sewage lagoons. Their numbers are influenced mainly by BOD loading rates, and the depth and age of the lagoons. These factors act on populations through a combined effect of oxygen availability, food supply and substrate requirements. Midges do well in any situation where the D.O. is normally above 1 ppm and are able to survive varying periods of anoxic conditions depending upon the temperature.

Kimerle and Anderson (1971) in a study of larval midge populations in some midwestern stabilization ponds, reported that on

one occasion all the algae in a pond died and an anoxic condition developed which lasted for two days. The midge production in the pond was reduced from 53 cal $Kcal^{-1}$ day^{-1} to 23, but no increase in mortality was observed. This demonstrated the ability of the larvae to survive anoxic conditions for that period, and a resistance to soluble sulphides, methane and other toxic by-products produced by conditions of anaerobic decomposition.

Kimerle and Anderson (1971) found that midge populations thrived better in shallower water. In 1966, one lagoon was 1 m deep and only 30% of the total biomass of larval midges was confined to the 3 m-wide band at the edge of the pond. In 1967 the depth was increased to 1.5 m deep and 90% of the population was limited to the first 3 meters. Sturgess and Goulding (1968) observed similar trends in test lagoons. The reasons given as to why midges preferred the shallow water were two-fold. Conditions of low D.O. are less likely to persist in the shallows because some mixing will take place, and light is able to penetrate in shallow water, providing food in greater abundance at the bottom where the midges live.

No explanation seems to be available for the observation that older lagoons are less productive. Accumulation of organic materials on the bottom creating toxic conditions seems the most logical explanation (Kimerle and Enns, 1968). Mitchell and Listowell have operated more than ten years in Ontario with no apparent reduction in midge production.

Different species of midges have been found to inhabit lagoons at different loading rates. Kimerle (1968) divided lagoons into three categories according to BOD loading, and reported that ponds with a mean loading of 18.3 lb/acre/day were inhabited by G. *barbipes*, at 32 lb, C. *plumosus* was dominant and at 50 lb, T. *punctipenis* was the principal species.

No studies have been made of midge species inhabiting Ontario lagoons, although the author has noted different species to be present in various lagoons observed. Loading rates to ponds selected for review for this paper indicated a range of 13.7 to 51.0 lb/acre/day, so that rates are within the ranges previously found to be acceptable.

The organic loading rate ultimately controls the population of both midges and daphnia as it is the source of raw materials that feeds the system. It is expected, therefore, that there will be an optimum loading for the species to be cultured which will establish the upper limit of production.

The lower limit will be set by the elimination of anoxic conditions when populations are not limited to a few pollution-tolerant species. When predatory midges, beetles and fish are able to populate the pond, a much lower rate of production of the crop to be harvested would be obtained. It is desirable, therefore, to load ponds to near the tolerance level of the species to be cultured and allow short periods of anoxic conditions to develop to control predators. Osmond (1971) reported the presence of the phantom midge *Caoboris sp.*, a predator, in the Mitchell sewage lagoons. The average loading to these ponds was 15 lb BOD/acre/day, but the three ponds operate in series and the loading and biota represent various stages of purification.

3. SEWAGE LAGOONS IN ONTARIO

There are approximately 85 municipalities using lagoons as waste treatment systems in Ontario, with a total acreage of ponds in excess of 2000 acres. They range in size from a single cell of less than an acre to the six-cell installation of 109 acres at the town of Lindsay. The early design criteria were based on continous flow and a loading of 20 lb of BOD/acre/day, or approximately 100 persons/acre. Allowances were often made for increased hydraulic flows and with time many of the communities served have increased populations or have had industries with high waste loads establish within the municipality. In some instances, the area of the lagoons has been increased to provide for the additional load or aerated lagoons have been added to reduce the loading on existing ponds. Others have not added sufficient capacity and have been operated in an overloaded condition.

Following the requirement for phosphorus removal, many continuous overflow systems have been operated on a seasonal retention basis with batch treatment in both spring and fall. Spray irrigation of seasonal lagoons has also been practiced on an experimental basis or as a solution in certain critical areas. A number of municipalities are also using a continuous feed of chemicals as a means of reducing phosphorus where convenience is a factor or seasonal retention is not possible.

Good operating information on sewage lagoons is not available. As they require little day-to-day maintenance and operation, such simple information as temperature, dissolved oxygen conditions, pH or regular chemical data from raw and effluent samples are largely unavailable.

In assessing the potential for effluent improvement through harvesting of biota from sewage lagoons under Ontario conditions, a review of records of analyses performed on lagoon effluents or pond contents during the open water season was made. Only five lagoons were found to have sufficient records to be useful. The data from these are summarized by year (Tables 5 to 9 - Appendix), and a comparative summary prepared for the five ponds selected (Table 1). To obtain the best influent data, year round results were used as the character of the influent should not change appreciably. Winter pond quality is not pertinent to this study so that May to October data were selected.

TABLE 1. PHYSICAL-CHEMICAL DATA SUMMARY

INFLUENT - mean annual | EFFLUENT: May-October

Lagoon	Retention Acres	Retention Days	No. of Samples	BOD lb/day	BOD ppm	Total Kj	Total P	No. of Samples	BOD	Total Kj	Total P	Biota
Shelburne	13	55	26	24.0	133	29.0	8.4	14	29.9	13.7	2.2	Midge Daphnia
Lindsay	109	80	19	13.7	112	27.7	10.4	16	19.5	6.5	3.7	Unknown
New Hamburg	28	164	25	25.0	421	54.4	15.4	12	16.7	10.3	3.4	Midge
Mitchell	66	104	10	15.0	165	20.6	7.9	4	5.9	2.5	1.5	Midge
Listowell	69	66	31	51.0	334	26.6	5.4	19	28.6	9.9	2.8	Midge
Mean				25.7	233	31.7	9.5		20.1	8.5	2.7	

Concentration in ppm unless otherwise indicated

No. of samples - average per year.

Influent - N/P = 3.3/1

Effluent - N/P = 4.3/1

Phosphorus removal is the most important criteria to consider as Ontario now requires that the total phosphorus be less than 1 ppm in discharges from most lagoons. Table 1 indicates that under existing operating conditions, a reduction from 9.5 ppm to 2.7 ppm occurs during summer operation, a removal of 72%. An additional removal of 1.7 ppm by biological harvesting would, therefore, be required if the phosphorus limit was to be met.

Nitrogen has generally been measured as Total Kjeldahl. While this does not include nitrates or nitrites, their general level has been found to be low and would not change the total nitrogen levels appreciably. The average Kj nitrogen was 31.7 ppm in the influent and 8.5 in the effluent so that summer operating conditions brought about a reduction of 73%. BOD reductions through the lagoons were 90%.

No evaluation of environmental conditions with respect to the important parameters of dissolved oxygen, pH, temperature or sulphides have been made on Ontario ponds, so that no factual data are available to compare with published studies of lagoon biota. Likewise, no data on carbon resources are available to provide a C:N:P ratio for estimating maximum algae production. An approximation based on BOD loading could be calculated.

Considerable fluctuations occur in loading for all three parameters evaluated because of the nature of the raw sewage, varying retention times, and the character of biological responses. Culture programs would therefore have to be designed on the basis of the characteristics of individual systems.

4. POTENTIAL REMOVAL OF PHOSPHORUS, NITROGEN AND ORGANIC BIOMASS BY HARVESTING

Present conditions in sewage lagoons provide environments capable of maintaining rich cultures of algae and sometimes secondary production. An attempt in earlier sections of the report has been made to identify what is known of environmental constraints in the system based on information that could be gleaned from the literature and from personal observations. Increased production is undoubtedly possible in most lagoons by the application of current knowledge, such as balancing C:N:P ratios, adjusting flows and loadings to provide optimal conditions and simple modifications to the system. Polyculture to provide a series of harvestable products through a lagoon system could substantially increase the removal of nutrients.

While there are certain limitations in applying cultural practices to existing lagoons, there is some flexibility in multiple pond systems, and simple plastic curtains could be used to adjust areas within cells for practical experimentation.

In this section, an attempt will be made to quantify the potential for improving effluents, particularly with respect to phosphorus and nitrogen through harvesting of production. Unfortunately, the data for production and chemical content of organisms removed, upon which the theory of effluent improvement is based, are very limited. For this reason, certain liberties must be taken in transposing information from one species to another or applying broad averages. Nonetheless, this study is directed at the feasibility of the process and while the calculations may not be precise, they should be sufficiently accurate to determine whether the principle is worthy of further investigation. Reference will be made to required reduction of 1.7 ppm of phosphorus in the lagoon system. Table 1 shows that sewage lagoons now remove 72% but the effluent still contains 2.7 ppm. To meet the 1 ppm requirement, therefore, an additional 1.7 ppm or 17 lb must be removed from each million gallons or from each acre of 4 ft water.

4.1 Algae Removal

The most effective place to remove nutrients occurs in the algae stage, as the maximum biomass and production occurs here. In

spite of extensive investigations, (Cook, 1962; Golueke and Oswald, 1965), economical means of harvesting algae production have not been found.

On a theoretical basis, where nitrogen resources are fully utilized, a production of 400 to 1000 mg/l could be produced for each million gallons of sewage (Gotas et al, 1954). Fitzgerald and Rohlich (1958) report that maximum yield from sewage lagoons is 100 to 300 mg/l which is 1000 to 3000 lb (dry weight) per million gallons. The nitrogen and phosphorus content of sewage-grown algae is approximately 5.00% N and 1.25% P a ratio of 4/1.

If 2000 lb (dry weight) of algae were harvested per million gallons, 25 lb of phosphorus and 100 lb of nitrogen would be removed and the concentrations in the effluent would be reduced by 2.5 and 10 ppm, respectively (Table 2). This quantity would meet phosphorus removal requirements (17 lb) for all of the five lagoon systems summarized in Table 1, reduce nitrogen to less than 1 ppm and remove 2000 lb (dry weight) of organics which would otherwise be discharged.

4.2 Duckweed Removal

Harvey and Fox (1973), using data derived from laboratory experiments, calculated that one acre of sewage lagoons could produce 50 Kg of dried *Lemna minor* every four days, which is a production of 27.5 lb/acre/day (dry weight). They reported the analysis of the plants to be 0.8 ppm phosphorus and 4.6 ppm nitrogen. A calculation based on one hundred days' production indicates that 22 lb of phosphorus and 125 lb of nitrogen would be removed. This is in excess of the 17 lb phosphorus necessary to meet the 1 ppm effluent requirement.

4.3 Daphnia Removal

Calculation of production for daphnia in sewage lagoons is made difficult by lack of good standing crop information based on field data. DeWitt and Candland (1971) reported on the commercial harvest of daphnia from California stabilization ponds from which a calculated 1.5 tons/acre/month were harvested. This does not appear to have been a controlled experiment, but provides some guidance on the production and harvesting potential of a sewage lagoon. Using

TABLE 2. POTENTIAL PRODUCTION PER ACRE* (IN POUNDS)

Product	Standing Crop Wet	Standing Crop Dry	Production of Dry Weight in 100 days	Estimated Removal of Nutrients in 100 days Phosphorus	Estimated Removal of Nutrients in 100 days Nitrogen
Algae	20,000	2,000	**	25	100
Duckweed	4,677	222	2,750	22	125
Daphnia	566	57	1,000	11.2	92
Midges	1,200	132	500	5.6	46

* One 4-ft acre considered to equate to 1 mg.

** One harvest of total algal biomass provides required phosphorus removal.

TABLE 3. CHEMICAL COMPOSITION OF ORGANISMS (DRY WEIGHT BASIS)

Organism	% Phosphorus	% Nitrogen	Authority
Algae	1.25	5.0	Fitzgerald and Rohlich (1958)
Duckweed	0.80	4.59	Harvey and Fox (1973)
Daphnia	1.12	9.25	Baudouin and Ravera (1972)
Midges	1.12	9.25	Based on daphnia analyses

analyses of daphnia reported by Baudouin and Ravera (1972) of 1.12% p and 9.25% N, it may be calculated that phosphorus removal would be 11.2 lb and nitrogen 92 lb/acre during a 100 day production period. The total organic removal would be 1000 lb on a dry weight basis (Table 2).

On the basis of an average of 17 lb removal/acre required, this would be less than optimum but would meet the requirements for two of the five Ontario lagoon systems summarized in Table 1.

Dinges (1973) reports the findings of a study conducted on twelve sewage lagoons in Russia. The production of daphnia and moina was fifteen times that used for purposes of our calculation, which suggests that increased harvesting rates should be possible.

4.4 Midge Larvae Removal

Estimates of biomass and production of midge larvae have been made by a number of authors. The most significant papers are those of Nees and Dugdale (1959), Tubb and Dorris (1965), Kimerle and Enns (1968) and Sturgess and Goulding (1969). Some of the ponds investigated showed a marked concentration of midge larvae in the peripheral zone of the lagoon. Maximum standing crops of 5000 to 11,000 larvae per square ft were found by Sturgess and Goulding, 16,000 by Kimerle and Enns, and 4000 by Usinger and Kellen (1955) at the edges of lagoons. Porges and Mackenthun (1963) reported pond population to reach 956/ft^2 in northern Wisconsin ponds and Osmond (1971) measured 400/ft^2 in one southern Ontario pond.

Kimerle and Anderson (1971) showed production during the mid-June to mid-September period to be 33% of the standing crop per week. Based on 1200 lb of biomass, Osmond (1971), and 13 weeks' production, 5100 lb/acre of biomass would be produced in a summer season.

A second procedure can be used for measuring production based on a standing crop of 1200 lb/acre and life history information. Kimerle and Anderson indicate that 70% of the biomass at any one time is fourth instar larvae. Therefore, 840 lb/acre could be harvested in the approximately 20 days the larvae are in this stage, for a total of five harvests per season. Total production would, therefore, be 5 x 840 or 4200 lb/acre.

Based on an estimate of 11% dry matter (500 lb) and a larval composition of 1.12% phosphorus and 9.25% nitrogen, 5.6 lb of phosphorus and 46 lb of nitrogen would be removed with the 500 lb dry weight of organic material.

While this figure falls somewhat short of the desired phosphorus removal of 17 lb/million gallons, the production figures used are based on a biomass that is much lower than others found in the literature, and a tripling of production would provide phosphorus removal for three of the five ponds in Table 1. Adjustment of optimum loading and depth control could increase production severalfold and provide for the necessary removal. The use of artificial substrates to maintain the maximum population at an optimum depth for food supply and environmental conditions could greatly increase production and facilitate harvesting.

5. HARVESTING TECHNIQUES

The success of nutrient removal through harvesting will be dependent on an efficient and inexpensive method of removing production from the lagoons. Extensive studies on harvesting algae populations have been conducted in California by Golueke and Oswald (1965), although as previously indicated, no commercially viable system appears to have been developed. There remains the possibility, however, that new techniques might alter the economics of the process at any time. Dodd (1973) suggested the use of a paper pre-coated, belt-type filter and proposed that the filter and entrained algae be fed as a diet for ruminants. Wright and Luiz (1970) reported on a proprietary filter and provide amortized costs of operation. A breakthrough by such techniques could alter the economics sufficiently to make the harvesting and use of algae a practical means of nutrient removal from sewage lagoons.

Duckweed is a plant that has a high biological potential for reproduction and would lend itself to continuous culture in a system where an induced flow moved each day's production to a removal unit. Conventional vibrating screens would probably be an effective means of harvest. Ehrlich (1964) suggested the possibility of a polyculture of duckweed and daphnia with the duckweed providing the shade for the daphnia. These two organisms have a similar turnover rate and could be harvested simultaneously with the same equipment.

Daphnia have been harvested in commercial fish culture programs and for tropical fish food, although little appears to have been published on the techniques used. As relatively small quantities were required, hand dip nets have generally been used. De Witt and Candland (1971) reported on collections made by pumping pond contents through a screening device. At a rate of 100 gal/min, up to 2 lb/min wet weight of daphnia were harvested. The attraction of daphnia to shade and yellow light reported by Dinges and Rust (1972) offers potential means of concentrating daphnia which could increase the efficiency of harvesting. Induced circulation within the pond to carry daphnia to a commercial vibrating screen would be a relatively low-cost removal method which could be adapted to large scale operations.

Midges are not known to have been harvested in quantity. They live on or near the surface of the bottom and the use of a suction dredge would appear to be the most practical collection device. A high-volume, low-head pump feeding a separator screen could be designed to retain fourth instar larvae and allow the smaller larvae to return for continued growth. Midge larvae have a smooth, waxy surface and are readily separated from sediments using differential floatation techniques which could provide a means for final cleaning and separation. The use of artificial substrates designed to provide the maximum surface for attachment offers a means of increasing production and facilitating harvest operations. A pump collector would also be used and less sediment and debris would have to be separated.

6. VALUE OF HARVESTED PRODUCTS

The economic value of harvested aquatic production can only be speculated, as major established uses and markets have not been developed. Likewise, the necessary analyses and feeding trials have not been performed to determine the conversion ratios of the protein, fats and carbohydrates in animals.

Plant products would most likely find a suitable market in formulations for domestic animal feeds. At the present time, plant proteins for animal foods have a value of 14¢/lb (pure protein basis, soya meal), lipids have a value of 10¢/lb and carbohydrates 5¢/lb. Based on these figures, the value of *Scenedesmus* (protein 32%, lipid 14% and carbohydrates 18%) should be $136/ton (Table 4).

TABLE 4. POTENTIAL VALUE OF HARVESTED PRODUCTS

Product	Production/acre	Value/acre	Remarks
Algae-Meal	2,000 lb	$80-$136	Estimated from components and alfalfa meal.
Duckweed-Meal	2,750 lb	$80	Based on alfalfa meal.
Daphnia-dry	1,000 lb	$250	Based on commercial fish food.
Midges-dry	500 lb	$125	Based on commercial fish food.

Golueke and Oswald (1965) indicated that sewage-grown algae are less valuable as animal foods than agricultural production because of digestibility problems, so that the estimated value is undoubtedly high and a spread between the theoretical maximum value and alfalfa meal has been given.

While no commercial use has been made of duckweed, a study by Limnos Limited under contract to the Ontario Ministry of the Environment has evaluated it in comparison with alfalfa meal and other aquatic plants. Chick feeding trials showed it to be equal to alfalfa meal as a replacement in formulated diets. On this basis, it would have a current value of $100/ton.

Daphnia and midge larvae have the advantage of being important sources of food to fish and waterfowl, so that there is little question as to their usability as an animal food product. Daphnia are presently harvested and sold live, frozen and freeze-dried for use in the culture of tropical fish and have been raised to provide food in hatchery operations for species such as maskinonge (*E. masquinongy*) and yellow pickerel (*S. vitreum*) which require live food in the early stages of culture. The production of these and other species is severely limited by the lack of assured quantities of zooplankton or other suitable natural foods and a ready market could probably be developed if supplies could be assured. DeWitt and Candland (1971) quote prices for frozen daphnia in California ranging from 15¢ to 80¢ per lb on the wholesale market, and $1.50 per lb on the retail market. Dried daphnia were sold in bulk on the retail market at $2.50 per lb. In Canada a 4 g freeze-dried package retails at 80¢, and supplies are largely imported from Taiwan. Frozen daphnia and midge larvae "bloodworms" in packages have a current wholesale value of $2.50 per lb in Toronto.

Any major production of daphnia would soon flood the pet food market and a more realistic value based on competitive feeds would be established. Commercial fish foods for hatchery use are presently worth 20¢ to 25¢ per lb, and a dry weight value of about this amount would be realistic. The value to the general feed industry would probably be comparable to fish meal, currently priced at about $250 per ton.

The value of midge larvae as a competitive fish food, or for inclusion in fish rations, is probably similar to that suggested for daphnia. Midges frequenting sewage lagoons have adapted to wintering in the larval stage and do not pupate during cold weather periods. It should be possible to maintain them in a live condition in cold water to provide an assured supply during off seasons, which would increase their value and usefulness for fish culture purposes.

Wild ducks, as ducklings and mature birds, utilize both daphnia and midge larvae from sewage lagoons. This would suggest that harvested production could have a value in domestic waterfowl production.

This report has not dealt with fish as a harvestable product from sewage lagoons. The potential for culturing and harvesting fish would not provide for a significant removal of nitrogen or phosphorus, since they represent the third step in a food chain and, thus, are unlikely to provide the necessary production to reduce nutrient levels. Production of minnows can, however, be in the order of 1000 lb/acre/season (wet weight) and would, therefore, constitute a valuable crop. There are potential markets for large scale production for both the bait industry and fish culture.

7. CONCLUSION

The potential exists for removing sufficient phosphorus to meet the one ppm total phosphorus requirement, from at least some Ontario lagoons, through culture and harvest of aquatic plant and animal production. Nitrogen would also be removed in a ratio of four to nine times that of phosphorus, depending upon the type of production harvested.

Further field studies are required to obtain reliable production estimates and analyses of the nutrient composition of the organisms, to confirm the information derived from the literature and estimates calculated from local data. The principal constraints on production appear to be reasonably well understood, so that through practical experimentation using existing facilities it would be possible to determine production potentials.

An evaluation of existing or modified equipment for harvesting the various forms of biota is necessary to determine the efficiency and cost. Evaluation of the harvested products is also required to determine their potential uses and value.

The estimated production and values represent the harvest of a single species, although several crops could undoubtedly be produced in a pond series. If the total nutrient resources of sewage were used, production would be approximately three times the values quoted, and six times if sewage was stored over winter and used the following season.

In considering the economics of nutrient stripping through culture and harvest, a self-sustaining cost should not necessarily be the criteria of success, at least in the initial stages, as current out-of-pocket expenses to the municipality are in the order of $100/acre (i.e. per million gallons) for one seasonal chemical treatment.

Phosphorus and nitrogen removals attributed in this study to the harvesting of biological production may include resources normally precipitated or lost to the atmosphere. Therefore, actual reductions due to harvesting may be lower than the levels postulated. However, effective harvesting would significantly restrict the internal recycling process and, as a supplement to precipitation, should greatly enhance effluent quality. The degree of enhancement which can be achieved must, however, be determined through practical field experiments.

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Problems today can be resources tomorrow. Sewage should be considered as a resource, and the author is grateful for having had the opportunity to consider the feasibility of one approach.

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APPENDIX

TABLE 5. PHYSICAL-CHEMICAL DATA - SHELBURNE

SHELBURNE - 13.2 acres

	Influent						East Lagoon Effluent - (Summer)			
Year	No. of Samples	Mean Daily Flow (mil gal)	BOD lb/acre/day	BOD ppm	Total Kjeldahl	Total Phosphorus	BOD	Total Kjeldahl	Total Phosphorus	No. of Samples
1970	4	.20	25	170			24.25	6.45	2.6	4
1971	32	.197	26	150	30	12	Cont. feed started			
							(Oct.)	(Oct.)	(Oct.)	
1972	10	.23	24	137	23	8.9	27.5	10.25	2.4	4
1973	40	.29	24	107	25	6.74	37.7	14.75	1.23	26
1974	43	.264	20	103	37.0	6.0	30.2	23.2	2.7	24
Mean	26	.236	24	133	29	8.4	29.9	13.7	2.2	14.5

Influent: N/P = 3.5

East Lagoon: N/P = 6.2

Average retention time: 55 days

West Lagoon

		Effluent - (Summer)			
		BOD	Total Kjeldahl	Total Phosphorus	No. of Samples
		(Oct.)	(Oct.)	(Oct.)	
	1972	27	10.3	4.5	4
Continuous feed started	1973	32	10.9	.9	23
	1974	33	17.7	1.3	24
	Mean	31	13	2.3	17

N/P = 5.7

TABLE 6. PHYSICAL-CHEMICAL DATA - LINSDAY.

LINDSAY - 109 acres

		Influent					Effluent - (Summer)			
Year	No. of Samples	Mean Daily Flow (mil gal)	BOD lb/acre/day	BOD ppm	Total Kjeldahl	Total Phosphorus	BOD	Total Kjeldahl	Total Phosphorus	No. of Samples
1970	9	1.3	14	130	25	13	20.7	4.64	3.72	5
1971	10	1.42	15	120	24	10	35.5	7.65	4.49	10
1972	43	1.36	13	100	24	9.7	10.7	7.72	4.01	22
1973	13	1.36	13	100	37	8.8	11.26	6.04	2.70	26
Mean	18.75	1.36	13.75	112.5	27.75	10.37	19.54	6.51	3.73	15.75

Influent: N/P = 2.67

Effluent: N/P = 1.93

Average retention time: 80.14 days

TABLE 7. PHYSICAL-CHEMICAL DATA - NEW HAMBURG

NEW HAMBURG - 28 acres

	Influent						Effluent - (Summer)			
Year	No. of Samples	Mean Daily Flow (mil gal)	BOD lb/acre/day	BOD ppm	Total Kjeldahl	Total Phosphorus	BOD	Total Kjeldahl	Total Phosphorus	No. of Samples
1970	36	.18	27	500			15.36			11
1971	19	.155	23	420			17.2	5.4	3.2	12
1972	28	.19	30	420	58	20	16	8.5	4.9	10
1973	24	.16	31	540	62	17.2				
1974	17	.17	14	225	43.25	8.85	18.4	17	2.24	17
Mean	25	.17	25	421	54.4	15.4	16.7	10.3	3.4	12.5

N/P = 3.5 (influent)

N/P = 3 (effluent)

Average retention time: 164.7 days

TABLE 8. PHYSICAL-CHEMICAL DATA - MITCHELL

MITCHELL - 1970: 41.6 acres
1971 and later: 66 acres

		Influent					Effluent - (Summer)			
Year	No. of Samples	Mean Daily Flow (mil gal)	BOD lb/acre/day	BOD ppm	Total Kjeldahl	Total Phosphorus	BOD	Total Kjeldahl	Total Phosphorus	No. of Samples
1970	8	.49	12	100			5.75			2
1971	9	.523	15	200	16	6.4	2.4	1.6	1.7	4
1972	11	.61	20	200	26	11	6.48	4.18	1.9	7
1973										
1974	10	.54	13	160	19.9	6.4	9.0	1.75	.75	2
Mean	9.5	.54	15	165	20.6	7.9	5.9	2.5	1.5	3.75

Influent: N/P = 2.6

Effluent: N/P = 1.66

Average retention time: 103.55 days

TABLE 9. PHYSICAL-CHEMICAL DATA - LISTOWELL

LISTOWELL - 69 acres

	Influent						Effluent - (Summer)			
Year	No. of Samples	Mean Daily Flow (mil gal)	BOD lb/acre/day	ppm	Total Kjeldahl	Total Phosphorus	BOD	Total Kjeldahl	Total Phosphorus	No. of Samples
1970	20	.96	53	360			40.72			11
1971	28	1.13	52	320	33	6.9	36	11.25	4.2	12
1972	48	1.1	70.1	440	25	5.0	30.09	8.42	3.41	26
1973	42	1.0	45	310	23	4.5	13.81	8.87	1.60	26
1974	21	1.04	36	240	25.4	5.4	12.67	11.26	2.20	20
Mean	31	1.04	51	334	26.6	5.45	28.65	9.95	2.85	19

Influent: N/P = 4.88

Effluent: N/P = 3.49

Average Retention time: 66.34 days